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ECOLOGICAL SCIENTISTS' DECISION-MAKING UNDER UNCERTAINTY AND IGNORANCE: IMPLICATIONS FOR BIOLOGY EDUCATION

Hyojeong Hwang,
Jun-Ki Lee

Abstract. *Ecological scientists routinely make decisions in contexts where scientific uncertainty and ignorance constrain available evidence, yet empirical research on how they judge such situations remains limited. Understanding these decision-making processes is critical because ecological crises—such as biological invasions and chemical accidents—require rapid action despite incomplete information. Accordingly, this study aimed to examine how ecological field experts respond cognitively, emotionally, and behaviorally to different uncertainty-laden scenarios. The study involved 16 ecological field experts from a single national context (with an average experience of 22.0 years), specializing in amphibians, reptiles, freshwater fish, and birds. Data were collected using three scenario-based instruments representing increasing levels of uncertainty, risk, and urgency, and analyzed through constant comparative analysis. Four distinct decision-making types emerged: Consistent Knowledge-Seekers (25.0%), Risk-Escalating Responders (25.0%), Action-Oriented Responders (25.0%), and Policy-Focused Responders (25.0%). As risk increased across scenarios, the research orientation decreased from 93.8% to 43.8%, while the preventive/management orientation increased to 56.2%. Additionally, emotional responses intensified to 25.0% in the high-risk scenario. These findings underscore the importance of biology education in leveraging uncertainty as a learning resource and fostering students' contextual scientific reasoning, adaptive expertise, and communication competencies.*
Keywords: *post-normal science, scientific uncertainty, scientific ignorance, ecological experts, decision-making patterns, adaptive expertise, biology education*

Hyojeong Hwang
Chungnam National University, Republic of Korea
Jun-Ki Lee
Jeonbuk National University, Republic of Korea

Introduction

Contemporary scientific practice operates in a complex environment of uncertainty, value conflicts, high stakes, and urgent decision-making. This terrain extends well beyond traditional models of certainty and objectivity (Edwards, 1990; Fischhoff & Davis, 2014; Tan & Koh, 2022; Wessels et al., 2022). Contemporary societal challenges, including climate change, biodiversity loss, the spread of invasive species, the emergence of infectious diseases, and the risks associated with novel chemicals, are all characterized by a complex interplay between scientific uncertainty and social risk (Pietrocola et al., 2021; Schwenkenbecher et al., 2023). This reality demands a paradigm shift in the conceptualization and teaching of science. Science is no longer confined to pure inquiry within laboratory walls, but has become inextricably linked to social context and real-world decision-making (Medvecky, 2022).

The concept of Post-Normal Science (PNS), as introduced by Funtowicz and Ravetz (1993), characterizes situations where "facts are uncertain, stakes are high, values are contested, and decisions are urgent." Beyond the confines of academic discourse, this framework outlines the prevailing operational modalities within contemporary domains, including ecology, environmental science, public health, and policy science. Post-Normal Science extends the remit of quality assurance in science beyond the peer review process among researchers, emphasizing the necessity of incorporating policymakers, stakeholders, and civil society in quality assurance processes. This recognition signals that science is no longer the exclusive domain of experts; democratic participation is imperative.

This standpoint is further elaborated upon by Ulrich Beck's risk society theory (2000), which posits that contemporary society is centered on the distribution and management of "manufactured risks" — hazards produced by industrial development itself. The uncertainty engendered by industrialization, technological advancement, and large-scale environmental interventions has given rise to a reappraisal of scientific authority, thus necessitating novel forms of governance and communication. Contemporary citizens are confronted with many scientific uncertainties, ranging from the unintended consequences of chemical substances to the long-term environmental impacts.

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Conventional science education has historically prioritized disseminating established knowledge and mastering verifiable methodologies, underpinned by the notion that "science pursues certain facts." Textbook content is frequently presented as facts, and learning has historically concentrated on students' acquisition of knowledge and its subsequent application. However, this approach falls short in accurately reflecting how science is conducted or how scientists arrive at judgments when confronted with incomplete information. Students often struggle to comprehend the intricacies of scientific uncertainty and limitations upon leaving formal education. This is often compounded by contradictory scientific media reports or policy inconsistencies, leading to student perplexity (Pietrocola et al., 2021).

The concept of "productive uncertainty", as proposed by Manz (2018), posits that students can conduct in-depth inquiry and exercise creative thinking in uncertain situations. Rather than an impediment to be surmounted, uncertainty can function as an educational resource that fosters deeper learning. For instance, the curiosity surrounding understudied biological species can catalyze more careful observation and reasoning, while situations of environmental pollution with unclear causation prompt students to examine multiple hypotheses. Through such processes, students recognize that the scientific pursuit is not one of final answers, but of continuous questioning and improvement.

Concurrently, studies on ignorance (see Proctor & Schiebinger, 2008; Gross & McGoey, 2015) have proposed an alternative reconceptualization of the concept of ignorance. Rather than perceiving it as a mere absence of knowledge, these studies propose that ignorance is, in fact, a "socially and organizationally produced and maintained phenomenon". Agnotology is the analysis of mechanisms that intentionally produce ignorance, tracing processes within policy, industry, media, and science where inconvenient truths are suppressed or uncertainty is deliberately amplified. Tobacco industries' dismissal of smoking health evidence and fossil fuel companies' emphasis on climate change uncertainty exemplify such dynamics. This standpoint asserts that education should foster critical thinking skills in students, encouraging them to reflect on the limits of their knowledge and the factors that contribute to their lack of understanding.

As evident from the existing research, the study focuses on theoretical discussions of uncertainty, teachers' conceptions, and measurements of student learning outcomes. Despite the extensive debate surrounding productive uncertainty, empirical analysis of how practicing scientists – particularly those in ecological and environmental specialties – judge situations, emotional responses, and actions within contexts of uncertainty and ignorance remains relatively scarce. Concrete examples of "adaptive expertise" that students should develop, and of professionals' actual management of uncertainty and ignorance, are required.

This research addresses this gap by conducting an in-depth qualitative analysis of ecological experts' scenario-based decision-making patterns and exploring implications for biology education. Comprehending how seasoned professionals identify knowledge deficits, liaise on research initiatives with operational activities, and navigate the emotional intricacies inherent in uncertain scenarios is vital. This profound understanding enables us to equip students more effectively with the necessary skills to make informed decisions in an unpredictable future.

The following research questions guide this study: Firstly, what immediate cognitive, emotional, and behavioral judgments do ecological experts express in each scenario (research gap, invasive species introduction, chemical spill)? The objective of this question is to determine how variations in expert responses are related to the characteristics of the scenario. Secondly, this study examines the relationship between knowledge gaps, forms of ignorance, and experts' research motivation and proactive management actions, clarifying how professionals transform uncertainty into action drivers. Thirdly, the study examines the impact of target characteristics, risk levels, and disciplinary alignment on decision-making strategies and emotional expressions, highlighting how situational variables influence expert judgment patterns. Fourthly, what implications do these expert decision-making patterns offer for curriculum design, lesson planning, assessment, and teacher professional development in biology education? This question is pivotal for aligning research findings with the improvement of educational practice.

Theoretical Background

Post-Normal Science and the Characteristics of Contemporary Science

Post-Normal Science asserts that conventional "normal science" is inadequate for circumstances characterized by elevated uncertainty, contested values, and substantial risks, necessitating fundamentally distinct scientific methodologies (Funtowicz & Ravetz, 1993; Saltelli et al., 2020). This paradigm shift entails augmenting quality management to encompass the involvement of policymakers, field practitioners, media representatives, and

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members of the general public. This development represents a departure from the conventional approach of relying exclusively on researcher peer review within the ambit of an extended peer community.

The field of ecology is one in which post-normal science is actively applied. In invasive species management, environmental pollution, and conservation policy, scientists must make urgent decisions based on incomplete evidence (Milner-Gulland & Shea, 2017). This reality renders the traditional linear procedure—accumulating evidence and then acting—practically impossible; research, action, and communication must co-occur.

However, despite extensive theoretical discussions on post-normal science, little is known about how ecological experts actually judge situations when evidence is incomplete. This gap directly highlights the need to examine the real-time judgment processes of ecological experts, which this study aims to address.

Risk Perception and Risk Governance

Slovic's (1987) seminal research on risk perception demonstrated that risk acceptance is contingent not solely on probability and loss calculations, but also on individual psychology, emotion, and sociocultural context. Two dimensions prove to be of particular significance: The terms "dread" and "unknown" denote states of heightened awareness, with the intensity of perception increasing concomitantly with both concepts. Risk is also known to undergo amplification or attenuation through social transmission processes (Kasperson et al., 1988).

The International Risk Governance Council (IRGC) and ISO 31000 present iterative risk governance structures (IRGC, 2017; ISO, 2018) that comprise a repeated pre-assessment, characterization, management, and communication cycle, with each cycle initiated by new information. This suggests the need for developing adaptive risk management systems, which necessitate collaboration among science, policy, and citizens.

This limitation underscores the need for empirical evidence on expert risk judgment in high-urgency ecological contexts.

Ignorance Studies and Agnotology

In their seminal work, Proctor and Schiebinger (2008) explored the concept of "agnotology", which is defined as the analysis of "cultures of ignorance". This term refers to instances where ignorance is deliberately produced and sustained. Examples of such cases include the tobacco industry's suppression of smoking-related health evidence, the fossil fuel industry's emphasis on climate uncertainty, and the pharmaceutical industry's suppression of unfavorable research. Rayner's (2012) analysis examined the phenomenon of organizations evading "uncomfortable knowledge, " which manifests in scientific institutions, government entities, and corporate bodies.

Agnotology, defined as the study of the production and maintenance of ignorance, holds profound educational significance. It mandates that students move beyond recognizing their own ignorance to critically analyze the social and historical factors that perpetuate it, the groups that benefit from it, and the consequences that follow.

Understanding how experts manage ignorance in practice is therefore essential for building an empirically grounded model of decision-making under uncertainty.

Productive Uncertainty and Science Education

Manz (2018) proposed teaching strategies that transform uncertainty into momentum for student learning. Forming hypotheses, testing these hypotheses, and gaining a deeper understanding through failure are all hallmarks of authentic scientific practice. Teacher roles involve reframing uncertainty not as evasion, but as an opportunity for exploration, with ongoing support for student metacognitive reflection (Manz & Suárez, 2018).

Adaptive expertise, defined as the capacity to adjust thinking strategies according to the demands of the situation (Kim & Gamble, 2022; Hatano & Inagaki, 1984; Saleh et al., 2023), encompasses more than mere extensive knowledge. It signifies the capacity to discern the most pertinent issue to address in novel situations, the applicable resources, and the necessity for strategic shifts.

This study addresses this gap by examining expert decision-making processes across scenarios involving uncertainty and ignorance.

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Research Aim and Research Questions

This research aimed to elucidate how ecological field experts navigate uncertainty and ignorance by qualitatively analyzing scenario-based decision-making patterns at different risk levels. This process aimed to identify distinct types of decision-making and their contextual variations. The study explored how teaching environments can foster responsible decision-making in uncertain contexts by translating these findings into educational implications. Four specific research questions guided the study:

RQ1: What immediate cognitive, emotional, and behavioral judgments do ecological experts express across scenarios of varying risk and urgency?
RQ2: How do knowledge gaps and ignorance connect with experts' research motivation and proactive management actions?
RQ3: How do target characteristics, risk levels, and disciplinary alignment affect decision strategies and emotional expressions?
RQ4: What implications do expert decision-making patterns offer for biology education curriculum, lesson design, assessment, and teacher professional development?

Research Methodology

Participants

This study employed a naturalistic qualitative research methodology (Creswell, 2018; Yoo et al., 2012). The sixteen participants were ecological field experts specializing in amphibians, reptiles, freshwater fish, and birds, with research experience ranging from 11 to 35 years (mean = 22.0 years, median = 20.0 years). They all worked in universities, government, or private research organizations and were actively engaged in ecological surveys, data analysis, policy consultation, and field management.

The expert group consisted of five university faculty members, seven researchers affiliated with national research institutes or university-based research centers, and four practitioners working in private ecological organizations, associations, or environmental consultancies. Their professional responsibilities included long-term biodiversity monitoring, species and habitat assessments, conservation planning, and responding to environmental incidents. Although all participants were situated within a single national context, this institutional diversity ensured that multiple perspectives within applied ecology were represented in the sample.

Instruments and Scenario Development

To examine how ecological experts navigate contexts of uncertainty and ignorance, this study developed three scenario-based research instruments that progressively escalate in levels of uncertainty, risk, and urgency. Each scenario was designed to prompt immediate, unrehearsed expert judgments that reflect genuine decision-making processes in real-world scenarios of varying complexity and significance (Wessels et al., 2022).

Table 1
Summary of the Three Scenarios

Scenario	Description Summary	Risk Type
1. Research Gap	No studies exist on a familiar species	Academic
2. Invasive Species	Species X is spreading; hazards unknown	Ecological/Social
3. Chemical Spill	Chemical Y released; toxicity unknown	Hazardous/Chemical

The first scenario addressed research gaps and knowledge deficits in the field of ecological science. Participants were presented with the following: 'You are conversing with colleagues in your field. Your discussion concerns a species you regularly study. During the conversation, you discover that virtually no research papers exist on this species.' This scenario was deliberately constructed to represent a context of low urgency characterized primarily by academic uncertainty. It emphasizes the absence of knowledge in the absence of immediate risk or time pressure,

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providing a context in which to examine how experts interpret unmet research needs, and whether they perceive such gaps as barriers to understanding or opportunities for scientific contribution. It encompasses characteristics of low urgency and academic uncertainty, offering a substantial scope for exploration and making it an ideal instrument for examining research motivation and collaborative inquiry orientation.

The second scenario addressed the introduction and spread of invasive species with unknown ecological impacts. Participants received the following description: 'Species X is not native to this country. The hazards of Species X have rarely been studied domestically or internationally. One day, news reports state that Species X has recently invaded the country and is spreading.' This scenario introduced moderate urgency alongside ecological and social risk dimensions. It presents a context in which species invasion occurs, but prevention remains feasible if timely action is taken. Experts had to navigate the tension between insufficient research and the necessity for action, deciding whether immediate containment measures should precede a complete hazard characterization. The scenario was designed to represent moderate urgency and ecological and social risks involving environmental and societal dimensions, as well as realistic prevention possibilities through rapid response.

The third scenario presented a chemical accident involving unknown hazards. The scenario description stated: 'Chemical Y was developed overseas. Chemical Y has recently been imported into this country. The hazards of Chemical Y have been rarely studied, either domestically or internationally. One day, news reports emerged that Chemical Y had been released in a vehicular accident.' This scenario embodied the highest risk and urgency levels of the three instruments. Despite incomplete knowledge about the chemical substance, it presented a crisis requiring an immediate response. Experts had to rapidly judge hazard severity and appropriate protective measures without a comprehensive scientific understanding. The scenario was designed to represent the following:

- High immediate urgency
- Invisible hazard characteristics typical of chemical substances
- The necessity for emergency response decisions despite insufficient knowledge

Data Collection and Analysis Procedures

After each scenario was presented, participants were instructed to express their thoughts, feelings, and reactions freely and without restriction or self-censorship. All verbal and written responses were meticulously documented and subsequently anonymized to protect the participants' identities and confidentiality. The text-based data collected were analyzed using constant comparative analysis methodology (Glaser & Strauss, 2017), a systematic approach that enables the iterative comparison and refinement of emerging concepts and categories.

The analysis progressed through three sequential yet iterative coding phases. In the first phase, open coding, response segments were systematically divided into meaningful units of analysis. Initial codes were generated using verb forms to emphasize process and action rather than static states or attributes. These initial codes captured the essence of expert judgments, decisions, and emotional responses reflected in the participants' discourse.

Subsequent axial coding involved comparing and integrating these initial codes to generate more abstract analytical categories. Five major analytical categories then emerged from the data through this comparative process. 'Research-oriented thinking' encompassed responses emphasizing inquiry, evidence gathering, and systematic investigation. The preventive/management orientation captured responses on risk mitigation, proactive measures, and management strategies. The emotional response category included expressions of anxiety, concern, confidence, and other affective states. Field action orientation represented responses prioritizing hands-on investigation, direct intervention, or an immediate practical response. The policy and communication orientation category captured responses emphasizing institutional change, regulatory frameworks, public communication, and governance structures.

In selective coding, the coded data were reintegrated into comprehensive narratives that captured the full context and complexity of expert decision-making. Scenario- and participant-specific response patterns were woven together to derive overall narrative structures illuminating how different judgment types emerged and shifted across scenarios of varying risk and urgency. This final phase yielded characterizations of distinct decision-making types and their contextual variations, providing a comprehensive understanding of expert cognition and judgment processes in uncertain contexts.

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Trustworthiness and Validity

Research trustworthiness and validity were ensured through multiple verification procedures that systematically addressed potential threats to credibility and confirmability. Researcher triangulation involved two independent researchers conducting parallel coding of selected response segments. After independently coding the data, the researchers compared their codes and resolved discrepancies through discussion and consensus-building. The resulting agreement percentages exceeded conventional thresholds, indicating strong inter-coder reliability.

Member checking involved presenting the analysis results and interpretations to a subset of participants from the original sample. These participants reviewed the proposed categories, judgment types, and overall findings, assessing whether the analytical framework accurately reflected their experiences and perspectives. Participant feedback confirmed the accuracy of the interpretations and provided opportunities to clarify or amend the preliminary findings.

Peer debriefing involved consultation with two external specialists — one with expertise in science education and one with expertise in ecology — who reviewed the analytical process, emerging categories, and final interpretations. The specialists examined whether the analytical approach was rigorous, whether the category definitions were coherent and internally consistent, and whether the final interpretations were logical conclusions of the presented evidence.

A comprehensive audit trail documented the analytical process, including initial coding schemes, category refinement decisions, framework modifications, and justifications for significant analytical decisions. This detailed documentation enabled external scrutiny of the methodological rigor and supported the assessment of replicability. The study achieved substantial credibility through these complementary validity procedures, ensuring the findings represent authentic expert perspectives rather than researcher artifacts or analytical impositions.

Research Results

Scenario 1: Research Gap

Quantitative Analysis and Primary Patterns

93.8% of experts (15 of 16) expressed research-oriented exploration responses to the research gap. This highest rate contrasted sharply with Scenarios 2 and 3 (56.3% and 62.5%, respectively). Preventive/management orientation was registered by only 6.3% (1 person), field action by 18.8% (3 people), and policy/communication orientation by 6.3% (1 person).

Qualitative Analysis and Representative Responses

Expert responses consistently demonstrated "awareness of knowledge gaps" and "reinterpretation as exploration opportunity":

"Learning of virtually no research on this species provides positive stimulus as a researcher. I would search similar taxon data, then systematically collect and analyze data. While difficult, a systematic approach when an opportunity exists is crucial." (Participant 1, Association Director)

> *"Recognizing the necessity of research on this species, I plan to formulate survey research protocols and conduct an investigation. I wish to collaborate with colleagues to create opportunities to fill this gap."*

(Participant 2, Professor)

> *"This presents an opportunity to pursue novel research. I could discuss research ideas concretely with colleagues in conversation and propose this theme to interested junior scholars for collaborative research." (Participant 3, Professor)*

These patterns align closely with Manz's (2018) concept of 'productive uncertainty'. Experts recognize uncertainty not as an obstacle, but as a catalyst for exploration, with repeated emphasis on 'collaboration,' reflecting Funtowicz and Ravetz's (1993) concept of an 'extended peer community.'

The educational implications are significant. Students encountering incomplete information or knowledge gaps should experience classroom cultures that enable them to transform these into learning opportunities. This represents shifting from one-directional knowledge transmission to active questioning and collaborative knowledge construction. In particular, the classroom question 'Why don't we yet understand this?' becomes a meaningful

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starting point for inquiry. Students will refine research questions through curiosity, locate the necessary resources, and collaboratively construct new understanding.

Scenario 2: Invasive Species Introduction and Spread

Quantitative Analysis and Primary Patterns

Decision patterns shifted substantially. Research orientation declined to 56.3% (9 people), while preventive/management orientation increased to 37.5% (6 people). Field action rose to 31.3% (5 people), and policy/communication reached 25.0% (4 people). Emotional response remained minimal at 6.3% (1 person).

This shift reflected a recalibration of judgment according to risk characteristics and increased urgency. Research remained necessary, but immediate action became critical.

Qualitative Analysis and Representative Responses

Expert responses emphasized "rapid response" and "precautionary principle":

> *"We must first determine how Species X invaded, from which country, whether artificial breeding or wild-caught individuals were distributed, and the quantity entered. Rapid prevention measures are necessary. Species lacking proven harmlessness should face legal import restrictions." (Participant 4, Research Institute Director)*

> *"Who will conduct Species X risk analysis? What effects and management strategies apply? Do similarities exist with bullfrogs or foreign snakes? These questions require systematic analysis." (Participant 5, Professor)*

> *"Whether X has established domestically, reproductive success, and expansion rates matter greatly. Simultaneously, confirming introduction pathways and proposing policy measures for rapid containment are necessary. Field investigation of actual conditions is urgent." (Participant 6, Professor)*

> *"Invasive species spread rapidly, requiring immediate monitoring and quarantine measures. Collaboration systems with relevant agencies must be immediately established." (Participant 7, Researcher)*

This scenario precisely aligns with the concept of "adaptive ecological management" proposed by Milner-Gulland and Shea (2017). As complete evidence cannot be accumulated for invasive species management, precautionary measures must be taken simultaneously while evidence is gathered, exemplifying authentic Post-Normal Science.

Participants referenced 'similar case precedents' (e.g., bullfrogs and foreign snakes), indicating that they make judgments based on historical experience and analogy when perfect scientific evidence is unavailable, which represents a realistic form of scientific reasoning.

This suggests that students must learn not merely to 'find certain answers', but also 'what to consider when making decisions with incomplete information'. Furthermore, the importance of 'collaborative governance' becomes evident, as research institutions, policy agencies, field practitioners, and citizens jointly address problems, thereby extending science education into democratic citizenship education.

Scenario 3: Chemical Spill Accident

Quantitative Analysis and Primary Patterns

The highest risk and urgency marked this scenario. Preventive/management orientation peaked at 56.3% (9 people), and research orientation remained substantial at 62.5% (10 people). Notably, emotional response increased dramatically to 25.0% (4 people)—substantially higher than Scenario 1 (12.5%) and Scenario 2 (6.3%).

Field action orientation declined to 18.8% (3 people) compared to Scenario 2's 31.3%, suggesting that the abstract and invisible nature of chemical substances elevates the importance of information gathering and communication relative to direct field action.

Qualitative Analysis and Representative Responses

Emotional elements are prominently featured alongside rapid communication and transparency emphasis:

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> *"Recognizing potential hazard, follow-up measures are necessary. Immediately notify emergency services and police for cooperation, determine resident evacuation necessity to prevent danger spread, and understand chemical dispersal modes and environmental factors to develop countermeasures." (Participant 1, Association Director)*

> *"Chemical Y hazard severity deeply concerns me. How Chemical Y might affect ecosystems and humans concerns me significantly. Rapid resident protection measures are necessary until hazard confirmation." (Participant 3, Professor)*

> *"Public education should occur regarding hazardous materials through media information provision. Accurate, rapid information proves central to trust recovery." (Participant 6, Professor)*

> *"Where Chemical Y is a new substance, hazard assessment must occur domestically. Import without such an assessment proves deeply concerning. Though overseas assessment may exist, domestic committee composition, hazard assessment, possibility confirmation, and safety assurance before import approval prove essential." (Participant 8, Professor)*

This scenario illustrates the operation of Slovic's (1987) theory of risk perception and the risk communication principles of Fischhoff and Davis (2014). Chemical spills, or 'invisible hazards', feature elevated dread and unknown dimensions, explaining the increased emotional response. Significantly, this emotional response transforms into 'responsible action' rather than panic. Despite anxiety, experts advocate "transparent communication", "rapid action," and "institutional improvement". This is an authentic manifestation of Funtowicz and Ravetz's (1993) emphasis on social responsibility.

The educational implications are profound. Firstly, scientific uncertainty does not invariably lead to calm and objective responses. Scientists experience anxiety, and this emotion can motivate them to take responsibility and action — insights that students require. Secondly, the importance of risk communication becomes evident: 'How things are said' matters beyond scientific facts; empathy and trust are equally important for conveying information. This goes beyond simple 'science communication' towards science education as 'civic responsibility'. Thirdly, there is a necessity for institutional improvement: scientific problems require more than scientific solutions; policy, legal, and governance improvements are essential.

Scenario-Specific Category Response Rate Analysis

Response patterns across the scenarios demonstrate systematic shifts in expert decision-making aligned with the situation's characteristics and risk level. A research-oriented approach dominated Scenario 1, accounting for 93.8% of the decisions. This declined to 56.3% in the moderate-risk Scenario 2 and partially recovered to 62.5% in the high-risk Scenario 3. Conversely, the preventive/management orientation increased progressively from 6.3% in Scenario 1 to 37.5% in Scenario 2 and 56.3% in Scenario 3. Emotional response intensity was sensitive to the invisibility of hazards, declining from 12.5% in Scenario 1 to 6.3% in Scenario 2 and then increasing dramatically to 25.0% in Scenario 3, which had invisible chemical hazard characteristics. Field action orientation peaked in Scenario 2 (31.3%) when visible, tractable ecological management was most relevant. However, it declined to 18.8% in Scenario 3, where invisible chemical hazards required information-based rather than field-based responses. These patterns demonstrate the sophisticated contextual adaptation of experts' judgment priorities according to situation-specific demands.

Table 2
Scenario-Specific Response Category Percentages and Trend Analysis

Response Category	Scenario 1 (Research Gap) [%(n)]	Scenario 2 (Invasive Species) [%(n)]	Scenario 3 (Chemical) [%(n)]	Trend
Research-oriented	93.8 (15)	56.3 (9)	62.5 (10)	↓↑
Preventive/management	6.3 (1)	37.5 (6)	56.3 (9)	↑↑
Emotional response	12.5 (2)	6.3 (1)	25.0 (4)	↓↑
Field action	18.8 (3)	31.3 (5)	18.8 (3)	↑↓
Policy/communication	6.3 (1)	25.0 (4)	12.5 (2)	↑↓

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Decision Type Analysis

Analysis of response patterns yielded four decision types, representing 25% of the expert group (four people), demonstrating balanced diversity. These distinct judgment patterns reveal multiple coherent approaches to uncertainty and ignorance. Despite shifting emphasis, each type maintains internal consistency across scenarios.

Table 3
Decision Type Distribution and Situational Characteristics

Decision Type	Proportion [%(n)]	Scenario 1 Characteristic	Scenario 2 Characteristic	Scenario 3 Characteristic	Educational Significance
Consistent Knowledge-Seekers	25 (4)	Research priority maintained	Research emphasis continued	Research necessity asserted	Academic rigor pursuit
Risk-Escalating Responders	25 (4)	Research-centered	Management intensified	Urgent response emphasized	Contextual awareness
Action-Oriented Responders	25 (4)	Research initiation proposed	Field measures prioritized	Rapid response emphasized	Practical wisdom development
Policy-Focused Responders	25 (4)	Long-term system necessary	Legal institutions strengthened	Regulatory protocols required	Democratic citizenship cultivation

The Consistent Knowledge-Seekers (Type 1) prioritized research and evidence accumulation across all scenarios without a fundamental shift in philosophy. These experts emphasized the importance of systematic inquiry, even as urgency increased, reflecting their conviction that understanding must precede or parallel action. Across three scenarios, Type 1 experts consistently articulated the importance of acquiring baseline scientific knowledge, developing research protocols, and accumulating evidence through collaborative investigation. Their approach reflects a deep commitment to academic rigor and scientific method, even under time pressure.

The Risk-Escalating Responders (Type 2) demonstrated flexibility in adjusting priorities according to contextual demands while maintaining underlying coherence. In Scenario 1, Type 2 experts emphasized research opportunities, whereas in Scenario 2, they shifted their focus toward management and prevention, and in Scenario 3, they concentrated on urgent protective measures. This type exemplifies adaptive expertise—recognizing context-dependent appropriateness of different strategies. Type 2 experts balanced short-term urgent response with long-term research and understanding, adjusting the emphasis dynamically.

The Action-Oriented Responders (Type 3) prioritized immediate damage minimization and practical problem-solving throughout all scenarios. Even in Scenario 1, where minimal urgency existed, Type 3 experts focused on "what can we do now" rather than fundamental research. In Scenarios 2 and 3, Type 3 experts emphasized the importance of rapid field investigation, containment measures, and practical mitigation strategies. Their approach reflects experiential wisdom and emphasis on real-world impact.

The Policy-Focused Responders (Type 4) consistently emphasized institutional and governance dimensions across scenarios. While recognizing the value of research and action, Type 4 experts stressed the importance of policy frameworks, regulatory structures, and systemic change. In all scenarios, these experts proposed legal standards, import regulations, and institutional improvements as necessary complements to research and immediate response.

These four judgment types represent coherent, internally consistent approaches to uncertainty and ignorance. No single type proves universally superior; each contributes essential perspectives to comprehensive problem-solving. The equal distribution (25% each) reflects a balanced representation of diverse judgment approaches within the expert community.

Discussion

Productive Uncertainty in Curriculum Design

The findings provide substantial empirical support for integrating productive uncertainty as a central pedagogical principle in biology education curricula. The present study has contributed to the existing literature on

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expert decision-making by offering a novel perspective on the role of uncertainty in understanding and knowledge construction. The present study's findings suggest that uncertainty is not a barrier to understanding but a catalyst for inquiry, creativity, and collaborative knowledge construction. This finding aligns with and extends the theoretical framework of productive uncertainty proposed by Manz (2018). This framework posits that students can conduct in-depth inquiry and exercise sophisticated scientific reasoning when confronted with authentic uncertainty contexts. The present findings advance the theoretical discourse in this field by providing concrete evidence that ecologists in practice transform uncertainty into motivation for systematic investigation, collaborative partnerships, and long-term research commitment.

Scenario-based instruction is an auspicious approach for operationalizing productive uncertainty within classroom contexts. Instead of presenting science as a static body of facts, scenario-based pedagogies situate learning within dynamic, evolving problem contexts that mirror authentic scientific practice (Hmelo-Silver & Barrows, 2008). Our research findings demonstrate that scenarios can be deliberately calibrated to vary in risk level, urgency, and target characteristics, enabling students to develop context-sensitive judgment capacities. The formulation of research gap scenarios raises fundamental questions for inquiry. The following questions are posed: firstly, in the absence of comprehensive knowledge, what approach should be adopted? Secondly, how can the unknown be approached systematically? Such scenarios are conducive to exploring design experiences in which students develop research protocols, formulate investigable questions, and recognize that uncertainty represents professional opportunity rather than failure. In the context of invasive species scenarios, there is a need to address situations where research is scarce, yet the necessity for management action is pressing. This creates a situation where there is a need to balance the lack of research with the requirement for management action. Such scenarios raise questions such as "How should decisions be made when information is incomplete?" and "What is the definition of adequate evidence for action to be taken?" These scenarios have fostered practical wisdom and decision-making skills, enabling effective operation within the constraints of real-world conditions. Chemical spill scenarios present high-urgency, high-stakes contexts that require immediate judgment and action, prompting students to consider the following questions: firstly, how should the organization respond rapidly while gathering information, and secondly, what ethical obligations are incumbent upon the organization in such crises?

The systematic relationship between scenario risk levels and expert response priorities provides crucial guidance for curriculum architecture. As the scenarios in question escalated in urgency and risk, the experts demonstrated a fluid recalibration of priorities, shifting from a focus on research to management and ultimately to communication. This dynamic adaptation indicates what Hatano and Inagaki (1984) term "adaptive expertise"—the capacity to adjust thinking strategies appropriately according to situational demands while maintaining underlying principles. Students derive considerable benefit from this dynamic recalibration process through the structured comparison of expert responses across various scenarios (Saleh et al., 2023). Metacognitive judgment reflection activities have been shown to help students identify their preferred judgment types (knowledge-seeking, action-centered, or policy-oriented) and understand how differing approaches prove more or less appropriate under varying circumstances. Discussing the advantages and disadvantages of different perspectives encourages meta-level cognition that transcends memorization towards adaptive reasoning (Ku & Ho, 2010). This is exemplified by questions such as "What are the benefits and limitations of prioritizing research in this situation?" and "When might action orientation prove more valuable than complete information gathering?"

The four-perspective team projects model real governance processes and provide significant opportunities for developing collaborative problem-solving skills. When students representing different judgment perspectives (research-focused, action-oriented, policy-focused, management-focused) work together on authentic ecological problems, they experience the productive tensions and complementarities that characterize real-world professional communities. This approach aligns with the sociocultural perspective in science education (Vygotsky, 1978; Wertsch, 1991), emphasizing that learning occurs through social interaction and participation in authentic practices. Such projects inherently engender the kinds of conflict negotiation, perspective-taking, and collaborative synthesis that constitute essential competencies for 21st-century scientists and environmental professionals (Krajcik & Blumenfeld, 2006). By encouraging students to embrace diverse viewpoints instead of pursuing a singular "correct" resolution, this pedagogical approach acknowledges the contemporary ecological challenges that necessitate contributions from researchers, practitioners, policymakers, and community representatives working in coordinated yet distinct roles.

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Ignorance Mapping Activity Implementation

The research findings revealed that ecological experts navigate uncertainty – areas of genuine knowledge limitation – and ignorance in the agnotological sense: socially constructed, politically shaped, and sometimes deliberately maintained knowledge gaps. The integration of ignorance mapping activities into biology curricula signifies a pivotal step towards cultivating critical science literacy, transcending the conventional paradigm of information transmission to embrace epistemological critique (Proctor & Schiebinger, 2008; Gross & McGoey, 2015; Liboiron, 2021). Students must be given opportunities to examine what is known and unknown in specific domains, why particular knowledge gaps persist, and who benefits from their maintenance.

Systematic ignorance mapping activities proceed through several interrelated phases. Initially, students enumerate and categorize uncertain aspects within specific ecological problems. For example, questions concerning the establishment dynamics of invasive species, the impacts of climate change, or the effects of emerging contaminants. In this phase, students distinguish between knowledge gaps that are genuinely difficult to address due to scientific complexity and those that may be deliberately overlooked due to industry interests or funding constraints. Subsequent causation analysis deepens this critical examination: The question, therefore, arises as to whether research insufficiency is indicative of genuine scientific difficulty or whether it is, in fact, a consequence of inadequate funding. The question arises as to whether interest gaps are the consequence of academic fashion or whether they reflect a deliberate downplaying of problematic issues. The question must therefore be posed: do technical limitations truly prove insurmountable, or have they been overcome in other contexts, but not applied here? The question arises as to whether we are witnessing the suppression of information, specifically scientific findings that institutions or corporations seek to conceal. Whether industry interests influence research agendas and resource allocation is crucial. The prevailing question is whether the apparent ignorance is, in fact, a consequence of excessive complexity, thus necessitating interdisciplinary approaches that have yet to be developed.

Through such systematic inquiry, students recognize ignorance as a socially constructed phenomenon reflecting distributions of power, resources, and institutional priorities – not merely as a neutral absence of knowledge. This critical perspective is congruent with the concept of "critical science literacy", as defined by Blenkinsop et al. (2016), which encompasses the comprehension of scientific content and understanding how science operates within societal and political contexts. After analyzing ignorance, students evaluate the impacts of particular knowledge gaps. Considering who benefits from this ignorance is important: corporations, governments, or special interest groups. Which policy decisions are hindered by a lack of complete knowledge? The present study explores the constraints imposed by ignorance on students and their communities. Consequently, reduction strategies are proposed: The question of who possesses the capacity to address particular ignorance is a complex one. What contributions might students make? The question that needs to be answered here is what would constitute adequate evidence for action.

This pedagogical approach directly addresses what Liboiron (2021) identifies as crucial environmental justice concerns in science education: namely, the recognition that some communities bear disproportionate consequences of scientific knowledge gaps and that marginal populations often lack the resources to conduct research addressing their pressing concerns. It is suggested that by helping students to understand how ignorance functions socially and politically, education in the biological sciences can cultivate commitment to more just knowledge production practices. Recent advancements in community-based participatory research (CBPR) and citizen science offer models through which students can meaningfully address knowledge gaps in domains that directly impact their communities (Vohland et al., 2021).

Risk Communication Competency Development

A particularly noteworthy and significant finding emerged regarding emotional responses in high-risk scenarios: expert anxiety and concern functioned not as obstacles to sound reasoning but as catalysts for intensified professional responsibility and protective action. This pattern presents a challenge to long-established traditions in science education, which have sought to cultivate "objective," emotion-free scientific reasoning (Fesmire, 2003; Pugh, 2002). The research demonstrates that emotional responses represent authentic, adaptive reactions to high-stakes uncertainty, transforming into motivation for comprehensive information gathering, protective measures, and transparent communication.

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This finding is consistent with mounting neuroscientific and psychological evidence that demonstrates an inherent interconnectedness between emotion and cognition, rather than an inherent opposition between them (Damasio, 1994; Immordino-Yang & Damasio, 2007). Emotional engagement has been demonstrated to facilitate deeper learning, stronger memory formation, and more motivated engagement, particularly for topics with personal or social significance (Pekrun & Linnenbrink-Garcia, 2014). In environmental and ecological subjects, students face risks to the ecosystems and communities they care about. Affective engagement is not a distraction from learning but a crucial component of meaningful and motivating science education (Sobel, 1996).

The emotional responses exhibited by our experts, characterized by expressions of concern regarding potential ecological and human health impacts, coupled with a resolute determination to mobilize protective action, illustrate what might be termed "responsible emotion" in the context of scientific practice. Rather than pathologizing such emotions as a threat to objectivity, this paper contends that science education should cultivate the capacity to channel emotions productively towards responsible action. This necessitates an explicit focus on what Watts and Alsop (2000) refer to as the "affective dimension of science teaching and learning," namely, acknowledging that emotions are integral and indispensable components of scientific citizenship.

Implementing risk communication competency development necessitates a range of classroom activities firmly rooted in authentic communication contexts and processes. Students must regularly practice composing concise, one-page briefings. This entails distilling intricate scientific data into its fundamental components, ensuring that the information is comprehensible to decision-makers constrained by time. Such exercises have been shown to foster the ability to communicate accurate scientific information efficiently in crisis communication scenarios, while also demonstrating an honest acknowledgment of uncertainty, as identified by Fischhoff and Davis (2014). The training in public message design maintains scientific accuracy while employing empathetic and accessible expression. Students learn the practical difference between technically precise but alienating language and comprehensible but potentially oversimplified messaging. The Q&A simulation exercise has been developed to prepare students for public interaction around uncertain or controversial scientific topics. The exercise emphasizes acknowledging unknowns without undermining credibility and maintaining transparency-based trust, even when definitive answers remain elusive.

Recent contributions to the social amplification of risk theory (Kasperson et al., 1988; Pidgeon et al., 2003) have demonstrated that risk perception and public response are contingent not only on technical hazard characteristics, but also on communication processes, institutional trust, and social dynamics. Science educators are increasingly aware of the need to cultivate the ability to communicate effectively about uncertain, risky, or controversial science, as this represents an essential competency for scientifically literate citizens (Howell & Brossard, 2021). The findings of this research demonstrate that ecological scientists prioritize effective communication and information sharing in high-stakes situations. This suggests that students should develop sophisticated risk communication competencies.

Teacher Professional Development Direction

Integrating research findings into teacher professional development programs requires providing support to teachers to facilitate fundamental shifts toward post-normal science perspectives and adaptive teaching practices. Teachers must possess a profound comprehension of post-normal science concepts and acknowledge the inherent uncertainty, value contestation, and urgent decision-making that characterize contemporary scientific challenges, often outside traditional research timelines. This represents a substantial paradigm shift from traditional conceptions of science as the pursuit of specific, universal, value-neutral knowledge (Latour, 2004; Shapin, 2010).

Acceptance of uncertainty and the development of an attitude conducive to it are paramount. However, these tasks are arduous for educators who have socialized into traditional scientific paradigms. It is incumbent upon teachers to examine and reconstruct their own relationships with uncertainty, moving from viewing uncertainty primarily as incomplete knowledge awaiting resolution toward recognizing uncertainty as a permanent feature of many scientific contexts. Reflection on personal experiences of uncertainty can facilitate teachers' modeling of uncertainty acceptance for students. Teachers have been shown to benefit from deliberate practice in responding to student questions with the statement, "Let us find out together," rather than positioning themselves as knowledge repositories. Such attitude shifts require more than intellectual assent; they necessitate emotional and identity work as teachers reconsider their professional roles and relationships with students (Clarke & Hollingsworth, 2002; Watts & Alsop, 2000).

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Recent literature on teacher adaptive expertise (Woulfin & Rigby, 2017) suggests that professional development should support teachers in developing flexibility in teaching approaches while maintaining pedagogical principles. Teachers must be given opportunities to comprehend how diverse instructional strategies, such as scenario-based learning, project-based inquiry, and collaborative problem-solving, serve distinct learning objectives and function appropriately under varying circumstances. Instead of seeking "best practices" that are universally applicable, it is incumbent upon teachers to develop contextual knowledge about when particular approaches prove most productive (Grossman et al., 2009).

The metacognitive teaching technique of mastery, which involves supporting students' explicit reflection on their thinking processes, is imperative for developing students' adaptive expertise. Teachers require substantial professional development in posing powerful questions that encourage student reflection without prescribing particular answers. To reach a decision, what information is required? To determine the most suitable approach, it is first necessary to consider how this would change if the risk level were higher. This study aims to ascertain the various trade-offs between different judgment strategies. The question to be addressed here is determining the point at which sufficient evidence justifies action. Pedagogical moves of this nature require sophisticated and pedagogical content knowledge, developed by teachers through sustained engagement with subject matter, instructional research, and reflection on practice (Shulman, 1986; Ball et al., 2008).

The analysis of actual crisis communication cases in conjunction with the simulation of media responses offers concrete contexts for the professional development of teachers (Bower et al., 2023). Instead of abstract discussion, it is more beneficial for teachers to examine real-world examples of how scientists, policymakers, and media professionals communicated during environmental or health crises. Which communication strategies have been proven to be effective? Identifying the point at which miscommunication occurred is the first step in resolving the issue. The investigation highlights how institutional trust – or the absence thereof – has influenced public response. Furthermore, teachers may also engage in simulated scenarios that require rapid responses to evolving crises, thereby experiencing firsthand the challenges of communicating under uncertainty and time pressure (Grecu et al., 2024; Zeyer & Adúriz-Bravo, 2025).

Conclusions and Implications

This research involved an in-depth qualitative analysis of the scenario-based judgments of 16 ecological experts, providing empirical clarification of how professionals think and act in contexts of uncertainty and ignorance. Several crucial findings emerged.

Firstly, the experts demonstrated situational adaptive judgment, adjusting their priorities to the circumstances and risk levels. This demonstrates that adaptive expertise constitutes a genuine functional capacity rather than an abstract concept. Research gaps highlight the need for exploration and inquiry, while the escalating invasiveness and chemical accidents necessitate a shift towards prevention, management, field action, and policy/communication. This flexibility transcends the rigid emphasis on principles in traditional science education, highlighting the need for contextual and adaptive thinking.

Secondly, the principle of post-normal science, which states that research and action must co-occur, was demonstrated in practice. Rather than waiting for complete proof, professionals simultaneously pursue evidence while implementing precautionary measures, demonstrating that linear scientific approaches — evidence accumulation followed by action — are often impractical in numerous situations. Similarly, biology education must train students to make judgments and take action based on incomplete information rather than waiting for perfect information.

Thirdly, the educational value of emotion has been recognized again. Anxiety, worry, and responsibility are not exclusively negative; they catalyze responsible action. Expert emotional responses to chemical spills — not panic, but manifestations of responsibility that translate into rapid response, transparent communication, and protection of residents — challenge the traditional notion of excluding emotion. Rather than avoiding emotions, students should learn to channel them towards constructive action.

Fourthly, diverse approaches such as knowledge exploration, immediate action, and policy improvement are all necessary; no single approach is "correct". Four types of judgment, distributed equally among experts (25% each), demonstrate substantial group diversity. Similarly, classroom education must respect diverse student perspectives and approaches, valuing each one.

These findings have profound implications for biology education. Rather than educating 'knowledge-possessing people', the focus should shift towards developing 'adaptive citizens capable of responsible judgment and

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action in uncertain situations'. This requires more than changes to the content, as it necessitates a transformation of the culture, teacher attitudes, and assessment systems. Education should leverage uncertainty as a learning resource, respect diverse perspectives, and provide opportunities for real problem-solving.

This research has certain limitations. The involvement of only sixteen ecological experts limits the generalization of findings to other scientific fields and broader populations. Scenario-based responses may differ from judgments made in actual field situations. Future research should verify the practical effects of the proposed educational strategies, track students' development of uncertainty competency longitudinally, and explore the potential applications of these strategies across various scientific fields and educational contexts.

Nevertheless, this research is significant in demonstrating, through actual expert judgment patterns, the directions in which biology education should progress. The core mission of contemporary biology education is to address uncertainty and fear of ignorance, treating them as opportunities for learning and growth, and cultivating respect for diverse perspectives and collaborative attitudes. Through such education, students can transcend mere knowledge acquisition to become mature science citizens, capable of taking responsible action within complex and uncertain worlds.

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Declaration of Interest

The authors declare no competing interest.

References

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content knowledge for teaching: What makes it special? *Journal of Teacher Education, 59*(5), 389–407. https://doi.org/10.1177/0022487108324554

Beck, U. (2000). The risk society revisited: Theory, politics and research programs. In B. Adam, U. Beck, & J. van Loon (Eds.), *The risk society and beyond: Critical issues for social theory* (pp. 211–229). Sage.

Blenkinsop, S., Telford, J., & Morse, M. (2016). A surprising discovery: Five pedagogical skills outdoor and experiential educators might offer more mainstream educators in this time of change. *Journal of Adventure Education and Outdoor Learning, 16*(3), 211–228. https://doi.org/10.1080/14729679.2016.1163272

Bower, M., Lee, M., & Dalgarno, B. (2023). The use of virtual simulations in teacher education to develop pre-service teachers' reflective practice. *Teaching and Teacher Education*, *121*, Article 103976. https://doi.org/10.1016/j.tate.2023.103976

Clarke, D., & Hollingsworth, H. (2002). Elaborating a model of teacher professional growth. *Teaching and Teacher Education, 18*(8), 947–967. https://doi.org/10.1016/S0742-051X(02)00053-7

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry and research design: Choosing among five approaches* (4th ed.). SAGE Publications.

Damasio, A. R. (1994). *Descartes' error: Emotion, reason, and the human brain.* Putnam Publishing.

Edwards, J. (1990). Rediscovering ignorance. *Research in Science Education*, *20*, 66–74. https://doi.org/10.1007/BF02620481

Fesmire, S. (2003). *John Dewey and moral imagination: Pragmatism in ethics.* Indiana University Press.

Fischhoff, B., & Davis, A. L. (2014). Communicating scientific uncertainty. *Proceedings of the National Academy of Sciences, 111*(Supplement 4), 13664–13671. https://doi.org/10.1073/pnas.1317504111

Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures, 25*(7), 739–755. https://doi.org/10.1016/0016-3287(93)90022-L

Glaser, B. G., & Strauss, A. L. (2017). Discovery of grounded theory: Strategies for qualitative research. Routledge. https://doi.org/10.4324/9780203793206

Grecu, M., Franks, E. E., & Boateng, G. O. (2024). Inclusive crisis communication in a pandemic context: A rapid review. *International Journal of Environmental Research and Public Health*, *21*(8), Article 1722. https://doi.org/10.3390/ijerph21081722

Gross, M., & McGoey, L. (Eds.). (2015). *Routledge international handbook of ignorance studies.* Routledge. https://doi.org/10.4324/9781315867762

Grossman, P., Compton, C., Igra, D., Ronfeldt, M., Shahan, E., & Williamson, P. (2009). Teaching practice: A cross-professional perspective. *Teachers College Record, 111*(9), 2055–2100. https://doi.org/10.1177/016146810911100905

Hatano, G. & Inagaki, K. (1984). Two courses of expertise. *Research and Clinical Center for Child Development*, 82–83 (Annual Report), 27–36.

Hmelo-Silver, C. E., & Barrows, H. S. (2008). Facilitating collaborative knowledge building. *Cognition and Instruction, 26*(1), 48–94. https://doi.org/10.1080/07370000701798495

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Howell, E. L., & Brossard, D. (2021). (Mis)informed about what? What it means to be a science-literate citizen in a digital world. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(15), e1912436117. https://doi.org/10.1073/pnas.1912436117

Immordino-Yang, M. H., & Damasio, A. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education. *Mind, Brain, and Education, 1*(1), 3–10. https://doi.org/10.1111/j.1751-228X.2007.00004.x

International Organization for Standardization. (2018). *ISO 31000:2018—Risk management: Guidelines*. Geneva: ISO.

International Risk Governance Council. (2017). *Introduction to the IRGC Risk Governance Framework: Revised version 2017*. EPFL International Risk Governance Center.

Kasperson, R. E., Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., Kasperson, J. X., & Ratick, S. (1988). The social amplification of risk: A conceptual framework. *Risk Analysis*, *8*(2), 177 –187. https://doi.org/10.1111/j.1539-6924.1988.tb01168.x

Kim, I., & Gamble, K. J. (2022). Too much or too little information: How unknown uncertainty fuels time inconsistency. *SN Business & Economics, 2*(2), 17. https://doi.org/10.1007/s43546-021-00189-9

Krajcik, J. S., & Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 317–333). Cambridge University Press https://doi.org/10.1017/CBO9780511816833.020

Ku, K. Y. L., & Ho, I. T. (2010). Metacognitive strategies that enhance critical thinking. *Metacognition and Learning, 5*(3), 251–267. https://doi.org/10.1007/s11409-010-9060-6

Latour, B. (2004). *Politics of nature: How to bring the sciences into democracy.* Harvard University Press.

Liboiron, M. (2021). *Pollution is colonialism.* Duke University Press. https://doi.org/10.1215/9781478021445

Manz, E. (2018). Designing for and analyzing productive uncertainty in science investigations. In *Rethinking learning in the digital age: Making the learning sciences count* (Vol. 1, pp. 288–295). University College London.

Manz, E., & Suárez, E. (2018). Supporting teachers to negotiate uncertainty for science, students, and teaching. *Science Education, 102*(4), 771–795. https://doi.org/10.1002/sce.21343

Medvecky, F. (2022). Public understanding of ignorance as a critical component of science literacy. *Sustainability, 14*(10), Article 5920. https://doi.org/10.3390/su14105920

Milner-Gulland, E. J., & Shea, K. (2017). Embracing uncertainty in applied ecology. *Journal of Applied Ecology, 54*(6), 2063–2073. https://doi.org/10.1111/1365-2664.12887

Pekrun, R., & Linnenbrink-Garcia, L. (Eds.). (2014). *International handbook of emotions in education.* Routledge.

Pidgeon, N., Kasperson, R. E., & Slovic, P. (Eds.). (2003). *The social amplification of risk.* Cambridge University Press.

Pietrocola, M., Rodrigues, E., Bercot, F., & Schnorr, S. (2021). Risk Society and Science Education: Lessons from the Covid-19 Pandemic. *Science & Education, 30*(2), 209–233. https://doi.org/10.1007/s11191-020-00176-w

Proctor, R. N., & Schiebinger, L. (Eds.). (2008). *Agnotology: The making and unmaking of ignorance.* Stanford University Press.

Rayner, S. (2012). Uncomfortable knowledge: The social construction of ignorance in science and environmental policy. *Economy and Society, 41*(1), 107–125. https://doi.org/10.1080/03085147.2011.637335

Saleh, M. R., Ibrahim, B. & Afari, E. (2023). Exploring the relationship between attitudes of preservice primary science teachers toward integrated STEM teaching and their adaptive expertise in science teaching. *International Journal of Science and Mathematics Education*, *21* (Suppl 1), 181–204 https://doi.org/10.1007/s10763-023-10369-8

Saltelli, A., Benini, L., Funtowicz, S., Giampietro, M., Kaiser, M., Reinert, E., van der Sluijs, J. P. (2020). The technique is never neutral. How methodological choices condition the generation of narratives for sustainability. *Environmental Science & Policy*, *106*, 87–98. https://doi.org/10.1016/j.envsci.2020.01.008

Schwenkenbecher, A., Hewitt, C. L., Heesen, R., Campbell, M. L., Fritsch, O., Knight, A. T., & Nash, E. (2023). Epistemology of ignorance: The contribution of philosophy to the science-policy interface of marine biosecurity. *Frontiers in Marine Science, 10*, Article 1178949. https://doi.org/10.3389/fmars.2023.1178949

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14. https://doi.org/10.3102/0013189X015002004

Slovic, P. (1987). Perception of risk. Science, 236(4799), 280–285. https://doi.org/10.1126/science.3563507

Sobel, D. (1996). *Beyond ecophobia: Reclaiming the heart in nature education.* Orion Society.

Tan, M., & Koh, T. S. (2022). Learning to become ignorant: Improving the quality of epistemic knowledge in science education. *Science Education, 107*(1), 9–27. https://doi.org/10.1002/sce.21753

Vohland, K., Land-Zandstra, A., Ceccaroni, L., Lemmens, R., Perelló, J., Ponti, M., Samson, R., & Wagenknecht, K. (2021). *The science of citizen science* (p. 529). Springer Nature. https://doi.org/10.1007/978-3-030-58278-4

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Harvard University Press.

Wals, A. E. J., & Jickling, B. (2002). "Sustainability" in higher education: From doublethink and newspeak to critical thinking and meaningful learning. *International Journal of Sustainability in Higher Education, 3*(3), 221–232. https://doi.org/10.1108/14676370210434688

Watts, M., & Alsop, S. (2000). The affective dimensions of learning science. *International Journal of Science Education*, *22*(12), 1219–1220. https://doi.org/10.1080/095006900750036226

Wertsch, J. V. (1991). *Voices of the mind: A sociocultural approach to mediated action.* Harvard University Press.

Wessels, K. R., Bakker, C., Wals, A. E. J., & Lengkeek, G. (2022). Rethinking pedagogy in the face of complex societal challenges: helpful perspectives for teaching the entangled student. Pedagogy, *Culture & Society, 32*(3), 759–776. https://doi.org/10.1080/14681366.2022.2108125

Woulfin, S. L., & Rigby, J. G. (2017). Coaching for coherence: How instructional coaches work to align instruction. *Educational Researcher, 46*(6), 323–329. https://doi.org/10.3102/0013189X17725525

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Yoo, G. W., Jung, J. W., Kim, Y. C., & Kim, S. H. (2012). Qualitative research methodology. Parkyoungsa Publishing.

Zeyer, A., & Adúriz-Bravo, A. (2025). Teaching Trust in Science: A Critical New Focus for Science Education. *Frontiers in Education*, *10*, Article 1164457. https://doi.org/10.3389/feduc.2025.1164457

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Hyojeong Hwang
School of Integrated Studies in Liberal Arts and Sciences, College of Creative Convergence, Chungnam National University, Daejeon, Republic of Korea.
E-mail: hjhwang@cnu.ac.kr

Jun-Ki Lee
(Corresponding author)
PhD, Professor, Division of Science Education, Biology Major, Institute of Science Education, Jeonbuk National University, 567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 54896 Jeonju, Republic of Korea.
E-mail: junki@jbnu.ac.kr
ORCID: https://orcid.org/0009-0006-7833-3712